

# A deep search for radio emission from three X-ray pulsars : are radio emission and X-ray pulsations anti-correlated ?

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## ABSTRACT

We present results from a deep search for radio emission from the X-ray pulsar systems GX 1+4, GS 0834-430 & 4U 0115+63 which have variously been suggested to possess radio jets and to be good candidates for propellor ejection mechanisms. None of these sources is detected at their optical positions, to  $3\sigma$  limits of a few hundred  $\mu$ Jy. This places upper limits on their radio luminosities and thus on the internal energy and numbers of any relativistic electrons which are three to four orders of magnitude below those of radio-bright X-ray binaries such as SS 433 & Cyg X-3. Spectral and structural information on the proposed ‘radio lobes’ of GX 1+4 make their association with the source unlikely.

The lack of detected radio emission from *any* X-ray pulsar system is discussed statistically, and it is found that X-ray pulsations and radio emission from X-ray binaries are strongly anti-correlated.

**Keywords:** X-ray pulsars, radio emission, GX 1+4, GS 0834-430, 4U 0115+63

## 1. INTRODUCTION

Radio emission is observed from  $\sim 10\%$  of X-ray binaries (e.g. Hjellming & Han 1995). It is generally assumed to be synchrotron in nature, characterised by high ( $> 10^8$  K) brightness temperatures and negative spectral indices ( $\alpha$ , where  $S_\nu \propto \nu^\alpha$ ). In at least eight cases radio (and in the case of SS 433, also optical) observations have revealed evidence for an origin in plasmons ejected from the systems at high velocities (see e.g. Fender, Bell Burnell & Waltman 1997 for a review). X-ray pulsations, indicating the rotation period of a highly magnetised accreting neutron star, are detected from  $\sim 15\%$  of X-ray binaries, mostly of the high-mass variety (e.g. White, Nagase & Parmar 1995).

To date, no radio emission has been detected from an X-ray pulsar system. In order to investigate whether or not this was simply bad luck or something more fundamental, we have chosen three unusual X-ray pulsar systems which might be expected to undergo significant mass loss, conceivably in the form of a jet:

- GX 1+4 is an unusual X-ray binary system containing a  $\sim 2$  min X-ray pulsar and an M-type giant (hence the ‘symbiotic X-ray binary’ nomenclature) (Chakrabarty & Roche 1997), with an unknown orbital period. The X-ray pulsar undergoes periods of both spin-up and spin-down as well as dramatic changes in luminosity (e.g. Makishima et al. 1988). In the case of Roche-lobe overflow, it seems that there should be significant mass-loss from the system (Chakrabarty & Roche 1997). Manchanda (1993) has suggested that two radio hot spots located roughly symmetrically about the optical position of GX 1+4 may be lobes resulting from the interaction of radio jets with the local ISM.
- GS 0834-430 is a 12 sec X-ray pulsar (Aoki et al. 1992) with a probable orbital period of 110.5 d (Wilson et al. 1997). No optical counterpart has been identified, so classification of the system is difficult, but it is probably a Be/X-ray binary system.
- 4U 0115+63 is a well known hard X-ray transient system containing a 3.6 sec X-ray pulsar in a 24.3 d orbit around a Be star (Rappaport et al. 1978), prone to large aperiodic outbursts, during which material may be ejected from the system (e.g. Negueruela et al. 1997).

## 2. OBSERVATIONS

We have observed GX 1+4 & GS 0834-430 at the same epoch with the Australia Telescope Compact Array (ATCA) at 20 & 13 cm, and 4U 0115+63 at

several different epochs with the Ryle Telescope (RT) at 2 cm.

### 2.1. Australia Telescope compact array

GX 1+4 & GS 0834-430 were observed on 1996 May 5 with the ATCA simultaneously at 20 & 13 cm. The array was in a compact configuration but also included the 6 km antenna. Total time on sources was 8.80 hr for GX 1+4 and 8.45 hr for GS 0834-430. Primary flux calibration was achieved using 1934-638, and secondary phase calibrators 1748-253 & 0823-500 were used for GX 1+4 & GS 0834-430 respectively. No signal more than  $3\sigma$  above the noise was detected at the optical position of either source. Maps of the source fields are presented in Figs 1 and 2 (we refer the reader also to Martí et al., these proceedings, who reports a marginal detection of a radio point source at the location of GX 1+4 with the VLA).

### 2.2. Ryle Telescope

Observations with the RT at 2 cm were made at two epochs in 1996. In the first, we attempted to look for orbitally phase-dependent transient emission, in particular around periastron. More recently we made a snapshot observation following BATSE detection of a brightening of the source. In all observations the primary flux calibrators were 3C48 and 3C286, and secondary phase calibration was achieved using B0106+678. Baselines ranged between 72m and 1.2 km.

- **Orbital coverage :** 4U 0115+63 was observed with the RT at 2 cm on the dates of 1996 Feb 9, 10, 11, 12, 15, 16, 17, 22, 23, 26 & 28. This covers phases 0.5 – 1.4, with periastron occurring around Feb 21 (based upon periastron passage on JD 2449598.6, and  $P_{\text{orb}} = 24.31$  d – Ignacio Neguerela, private communication). Individual observations detected no source to a limit of  $\sim 0.8$  mJy; mapping the data gives a significantly lower limit for the mean flux density (see Fig 3).
- **Observations during outburst :** Following the announcement by Scott et al. (1996) that 4U 0115+63 had gone into outburst on  $\sim$  1996 Aug 10, we made a further attempt to observe this source with the RT at 2 cm on 1996 Aug 16. Again there was no detection, to a  $3\sigma$  limit of 0.8 mJy.

## 3. DISCUSSION

### 3.1. Limits on synchrotron radio luminosity

For each source we can evaluate the limits on point-source emission given the distance to the source and some assumption about the spectrum of the emission. Based upon observations of radio-bright X-ray binaries we evaluate the luminosity limits for :

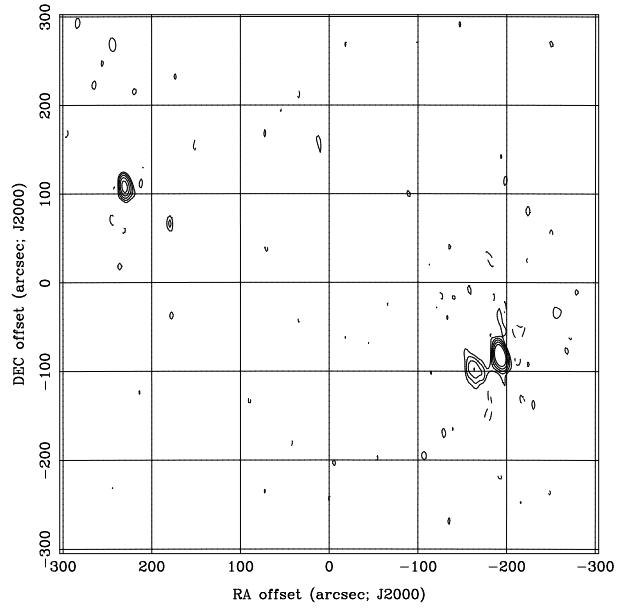


Figure 1: 20 cm ATCA map of GX 1+4 field. Contours are at  $-3, 3, 6, 12, 24$  &  $48$  times r.m.s. noise of  $130\mu\text{Jy}$ . The sources to the south-west and north-east of the pointing centre are hot spots ‘A’ & ‘B’ respectively of Manchanda (1993) – note that we have resolved ‘A’ into two components.

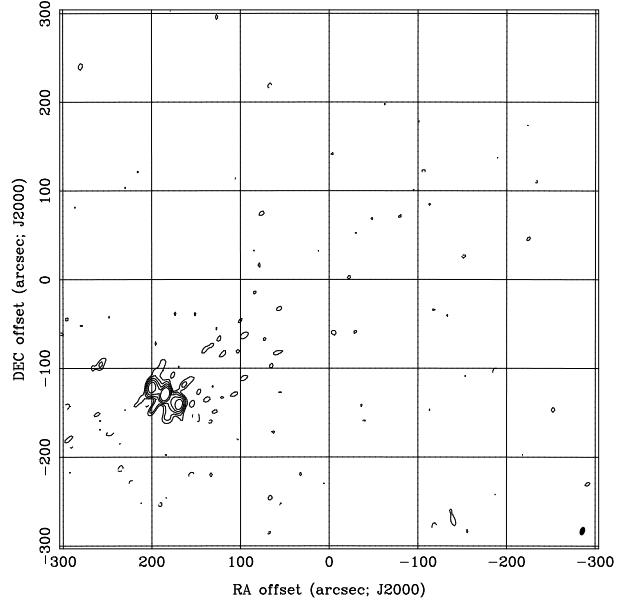


Figure 2: 20 cm ATCA map of GS 0834-430 field. Contours are at  $-3, 3, 6, 12, 24$  &  $48$  times r.m.s. noise of  $90\mu\text{Jy}$ .

Table 1: Observed flux limits and derived radio luminosity limits

Source	$\lambda$ (cm)	$3\sigma$ flux density limit (mJy)	Spectral index $\alpha$	Distance (kpc)	Radio luminosity limit ( $\text{erg s}^{-1}$ )	Total electron energy limit (erg)
GX 1+4	20	0.39	0.0	6	$3 \times 10^{30}$	$9 \times 10^{37}$
	13	0.24	-0.6		$4 \times 10^{30}$	$5 \times 10^{38}$
GS 0834-430	20	0.27	0.0	7	$4 \times 10^{30}$	$1 \times 10^{38}$
	13	0.24	-0.6		$5 \times 10^{30}$	$6 \times 10^{38}$
4U 0115+63	2	0.44	0.0	5	$7 \times 10^{30}$	$2 \times 10^{38}$
			-0.6		$2 \times 10^{31}$	$1 \times 10^{40}$

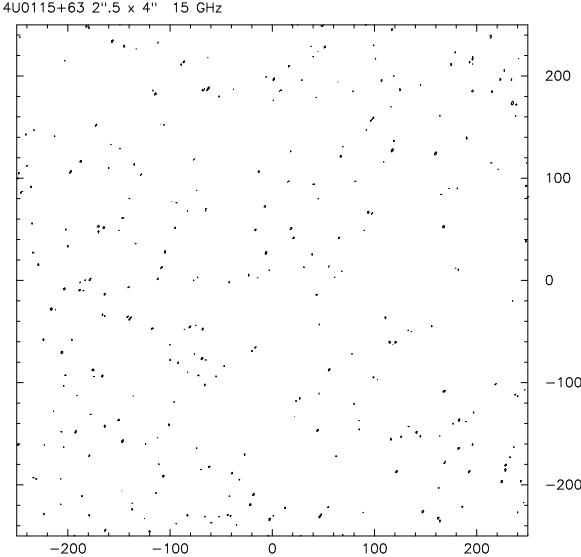


Figure 3: 2 cm RT map of 4U 0115+63 field. Contours are at  $-3$  &  $3$  times the r.m.s. noise of  $135 \mu\text{Jy}$ . Axes are arcsec offsets.

1. Optically thin synchrotron emission ( $\alpha = -0.6$ ), implying plasmon-dominated emission such as that observed in SS433.
2. Flat-spectrum core emission ( $\alpha = 0.0$ ), implying significant absorption at cm wavelengths, such as that observed for Cyg X-3 in quiescence.

Assuming isotropic emission, integrated radio luminosity is given by

$$L = 4\pi d^2 S_0 \nu_0^{-\alpha} \int_{\nu_0}^{\nu_1} \nu^\alpha d\nu \quad \text{erg s}^{-1}$$

where  $d$  is distance to source,  $\nu_0$  &  $\nu_1$  are lower and upper limits of integration respectively, and  $S_0$  is limit on flux at frequency  $\nu_0$  derived by extrapolating from observed limits. We choose  $\nu_0 = 5 \times 10^8 \text{ Hz}$  (60cm) and  $\nu_1 = 3 \times 10^{11} \text{ Hz}$  (1mm).

We can go one step further and place limits on the amount of energy in any relativistic electrons ejected from the sources. Tucker (1977) gives the following approximation for total energy :

$$U_R \sim 5 \times 10^{11} B^{-\frac{3}{2}} L \nu_*^{-\frac{1}{2}}$$

where  $B$  is the mean plasmon magnetic field (assumed to be randomly aligned),  $L$  is the radio luminosity integrated between frequencies  $\nu_0$  &  $\nu_1$ , and  $\nu_* = \nu_0$  for spectral index  $\alpha > -0.5$  and  $\nu_* = \nu_1$  for  $\alpha \leq -0.5$ .

Table 1 lists observed flux limits, implied radio luminosity limits and total relativistic energy limits (assuming  $B = 0.1 \text{ G}$  – see e.g. Spencer 1996) for both types of radio spectra, for all three sources. The electron energy limits correspond to  $\sim 5 \times 10^{44}$  electrons (for optically thin emission), implying a mass limit on the ejecta of  $\sim 10^{18} \text{ g}$  for an  $e^-e^+$  plasma, and  $\sim 10^{21} \text{ g}$  for an  $e^-p^+$  plasma.

For comparison, integrating the radio luminosities of the compact core ( $\alpha \sim 0$ ) of Cyg X-3 (in quiescence) and the optically thin emission of SS 433 ( $\alpha \sim -0.6$ ) between the same limits yields luminosities of  $\sim 3 \times 10^{33}$  and  $\sim 2 \times 10^{34} \text{ erg s}^{-1}$  respectively. Thus the three X-ray pulsars observed here are *at least* 500 times less luminous in the radio regime than radio-bright X-ray binaries. Spencer (1996) has also calculated  $U_R$  for five radio-emitting X-ray binaries and found that total electron energies are typically  $> 10^{41} \text{ erg}$ , three orders of magnitude greater than the limits placed here. Similarly, Mirabel & Rodriguez (1994) estimated the mass of a plasmon (assumed  $e^-p^+$  composition) ejected from GRS 1915+105 as  $10^{25} \text{ g}$  – four orders of magnitude more massive than the limit imposed by our observations.

### 3.2. GX 1+4 ‘jets’

As well as a limit on point source emission from GX 1+4, we also investigated hot spots ‘A’ and ‘B’ reported in Manchanda (1993) as possible radio lobes associated with the source. Whilst the apparent symmetry of the sources about the optical position of GX 1+4 is unusual, there is no hint of any collimated emission from the source to the lobes (Martí et al., these proceedings, confirms this result). Furthermore, we have resolved Manchanda’s westerly lobe, ‘A’ into two components, aligned roughly East-West, which have significantly different spectral indices.

### 3.3. Are radio emission and X-ray pulsations anti-correlated?

In *X-ray Binaries*, van Paradijs (1995) catalogues 193 X-ray binary systems; White, Nagase & Parmar (1995) state that there are 32 known X-ray pulsars, and Hjellming & Han (1995) list 22 radio-emitting X-ray binaries. Since this work,  $\sim 10$  new X-ray binaries have been found, at least one of which is an X-ray pulsar (GRO 1744-28 – no radio counterpart), and at least three of which are radio-emitting (GRS 1915+105, GRO J1655-40, GRS 1739-278). Furthermore, one previously known X-ray binary (GX 339-4) has been found to be radio-bright (see Sood et al., these proceedings). This gives  $\sim 200$  X-ray binaries, of which  $\sim 33$  are X-ray pulsars and  $\sim 26$  are radio-emitting. And yet radio synchrotron emission has *never been detected from an X-ray pulsar* (though it should be noted that sensitivity limits are not uniform across the sample). We do not consider here the possible radio detection of GX 1+4 as reported by Martí, these proceedings, as this is both (a) a marginal detection, and (b) consistent with thermal emission from the red giant wind in the system.

We can test the null hypothesis that radio emission and X-ray pulsations have no statistical connection against the alternative hypothesis that characteristics of radio emission and X-ray pulsations are strongly (anti-)correlated, defining the probability as

$$P = C(P_x P_r)^{n_{xr}} [P_x(1 - P_r)]^{n_{x'r'}} [(1 - P_x)P_r]^{n_{x'r}} [(1 - P_x)(1 - P_r)]^{n_{x'r'}}$$

where

$$C = \frac{n!}{n_{xr}! n_{x'r'}! n_{x'r}! n_{x'r'!}}$$

where  $n$  is the number in a population, and a subscript of  $x$  denotes X-ray pulsations,  $r$  indicates radio emission, and primes indicate non-membership of the group. We approximate the probability of being radio or X-ray emitting by their sample estimates,  $P_x \sim n_x/n$  and  $P_r \sim n_r/n$ .

We find that the probability of no X-ray pulsars lying in the radio-emitting X-ray binaries group, *if the two properties had no statistical connection*, to be  $3 \times 10^{-5}$ , i.e. if you had  $10^5$  samples of X-ray binaries, you would only expect the observed distribution to occur  $\sim 3$  times. We conclude that radio emission and X-ray pulsations from X-ray binaries are statistically anti-correlated.

## 4. CONCLUSIONS

We have performed a deep search for radio emission from three unusual and interesting X-ray pulsar systems. However despite deep dual-wavelength imaging of GX 1+4 and GS 0834-430, and monitoring of 4U 0115+63 around most of an orbit, including periastron, and within six days of a recent reported outburst, we find no evidence for radio emission from

these sources. The ‘radio lobes’ claimed to exist around GX 1+4 are confirmed, but one ‘lobe’ is resolved into two components, the spectral indices of all three components differ significantly, and there is no evidence of connecting radio structure tracing back to the optical location of the source.

These observations place strong limits on the radio luminosity and hence numbers, mass, and stored energy of any relativistic ejecta – three to four orders of magnitude lower than for radio-bright X-ray binaries. A simple statistical test shows that the current sample of X-ray binaries and the subsets of radio-emitting and X-ray-pulsing systems are sufficiently large that this lack of a radio-emitting X-ray pulsar system cannot be chance. In fact, it seems that the observable properties of detectable radio emission and X-ray pulsations from X-ray binaries are strongly anti-correlated.

We conclude that there appears to be some reason why X-ray pulsars are not radio-bright, and perhaps more significantly, that X-ray pulsars cannot form radio jets. This may be due to a lack of a stable inner accretion disc in systems containing a high magnetic field neutron star, or the material funnelling down field lines may somehow disrupt a nascent jet.

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